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The Monterey Bay turbulence model verification experiment was conducted to verify correlation models of bulk meteorological and optical turbulence (C_n^2). Laser scintillometer measurements were compared to predictions of the bulk model using meteorological data measured by R/V ACANIA. Results indicate that the model predicts optical C_n^2 to within a factor of two in homogenous cases.
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Block 20, Abstract, Continued

Satellite measurements suggest possible applications to verifying homogeneity for use of the bulk models.

The bulk model results did not correlate to optical measurements when infrared rather than bucket temperatures were used. Although three separate IR temperatures (surface, aircraft, satellite) agreed with each other, they seemed to be a bias of 1.5 degrees below the bucket temperature.

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TECHNICAL REPORT
TR 80-09

COMPARISON OF THE MARINE INDEX OF REFRACTION STRUCTURE PARAMETER, C_n^2, MODEL WITH OPTICAL MEASUREMENTS

Andreas K. Goroch
Naval Environmental Prediction Research Facility

DECEMBER 1980

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CONTENTS

1. INTRODUCTION

The 1980 Monterey Bay Turbulence model verification experiment was conducted to validate marine surface layer turbulence models to be used with the Navy High Energy Laser (HEL) program. The experiment consisted of laser scintillometer measurements across Monterey Bay accompanied by simultaneous shipborne bulk meteorology and turbulence measurements. In addition, an aircraft was flown to provide turbulence and meteorological measurements from near the surface to above the marine inversion, and GOES and DMSP satellite imagery was obtained in the visible and infrared channels.

The experiment verified that the marine surface layer turbulence model recommended to the HEL program by NEPRF (Burk, Goroch, Weinstein and Panofsky, 1979) agreed with the optical measurements to a factor of two. Experimental results indicate that the model depends on conventional bulk sea surface temperatures (platinum or bucket measurements) rather than infrared temperatures. Use of infrared temperatures in the model did not show any agreement with optical measurement. It is possible that a bias might be added to IR measurements to provide better agreement.

2. BACKGROUND

Turbulence in the atmosphere affects optical signal propagation by changing the resulting beam characteristics. The effect of turbulence is characterized by the optical index of refraction structure function, C_n^2, which is related to ambient meteorological conditions. The HEL program requested NEPRF to conduct a workshop to recommend a model correlating C_n^2 with meteorological parameters.

The recommended model is discussed thoroughly in the report of the workshop (Burk, *et al.*, 1979). Briefly summarized, the model modifies the bucket sea surface temperature for surface effects

$$T_{ss} = T_{ss}(\text{bucket}) - 0.025\ T_{air} - 0.1 \quad (V < 6\ \text{m sec}^{-1})$$

$$T_{ss} = T_{ss}(\text{bucket}) - 0.1\ T_{air} - 0.8 + V(0.117 + 0.0125\ T_{air}) \quad (V \geq 6\text{m sec}^{-1})$$

where T_{ss} (bucket) is the bucket sea surface temperature, T_{air} is air temperature, and V is 10 m wind speed. The following formulas provide the surface layer momentum heat and moisture fluxes in the form of scaling wind U_* temperature; T_* and specific humidity Q_*

$$U_* = kU[\ln(z/z_o) - \psi_n(z/L)]^{-1}$$

$$Q_* = \frac{k}{R}(q - q_s)[\ln(z/z_{oq}) - \psi_Q(z/L)]^{-1}$$

$$T_* = \frac{k}{R}(T - T_s)[\ln(z/z_{oT}) - \psi_H(z/L)]^{-1}$$

z_o - "roughness" parameter for momentum $\simeq$ 0.6 mm

z_{oQ} - "roughness" parameter for humidity

z_{oT} - "roughness" parameter for temperature

R - 0.74

k - von Karmann's constant 0.35

$$\left.\begin{array}{l} \psi_m = \ln[(\frac{1 + x^2}{2})(\frac{1 + x}{2})^2] - 2\arctan(x) + \pi/2 \\ \quad x = (1 - \gamma_m\ z/L)^{1/4} \\ \psi_H = \psi_Q = 2\ln[\frac{1 + \sqrt{1 - \gamma_H\ z/L}}{2}] \end{array}\right] \text{for } L \leq 0 \text{ (unstable)}$$

$$\left.\begin{array}{l} \psi M = -\beta\frac{z}{L} \\ \psi_H = \psi_Q = -\frac{\beta}{R}\frac{z}{L} \end{array}\right] L \geq 0 \text{ (stable)}$$

β = 4.7

γ_m = 16

γ_H = 9

The roughness parameters describe the detailed molecular interaction between the sea surface and the adjacent air. Their calculation is described in Burk _et al_., 1980.

The equations provided above are dependent on the Monin-Obukhov length L. The ratio of height z, to L is given by

$$\frac{z}{L} = \frac{gkT_*}{(T_{air} + 273.16)U_*^2}\left(1 + \frac{0.07}{B_o}\right)$$

where

g = acceleration due to gravity 980 cm sec^{-2}

B_o = Bowen ratio = $\frac{c_p}{L_H}\frac{T_*}{Q_*}$

c_p = specific heat of air

L_H = latent heat of evaporation of water

The above equations are solved by iteration. An initial value is assumed for L ($L = 1\cdot10^{30}_m$). The scaling parameters U_*, T_*, Q_* are calculated and L is recalculated and compared to the previous estimate. When two estimates agree to better than 0.1%, the temperature structure function parameter is

$$C_T^2 = \frac{T_*^2}{z^{2/3}}\, g(z/L) \qquad g\left(\frac{z}{L}\right) = \begin{cases} 4.9\left(1 + 2.75\,\frac{z}{L}\right) & L \geq 0 \\ 4.9\left(1 - 7\,\frac{z}{L}\right)^{-2/3} & L \leq 0 \end{cases}$$

and the optical index of refraction parameter is

$$C_n^2 = C_T^2\left[\frac{7.817\cdot10^{-5}\;p}{(T_{air} + 273.15)^2}\left(1 + \frac{.03}{B_o}\right)\right]^2$$

where p is air pressure in millibars.

This model was used with the surface correction and without for bulk meteorological variables, with platinum wire and infrared sea surface temperature measurements alternately.

3. EXPERIMENTAL PROCEDURE

The experiment consisted of two types of measurements: shore to shore optical scintillation measurements, and shipborne meteorology measurements. The measurement techniques are outlined below; complete descriptions are included in the reports of Crittenden, Milne, Rodeback and Kalmback (1980) and Davidson, Schacher, Fairall, Crittenden and Milne (1980).

4. OPTICAL MEASUREMENTS

The optical equipment consisted of a DF laser operating at 10.6 micrometers wavelength situated on the eastern shore of Monterey Bay. A chopped signal was sent along a 13.16 km path over Monterey Bay to a receiving station on the south west shoreline. The average height above the sea surface was 14 m. The optical range is shown in Figure 1.

The signal was measured for one minute to provide a distribution of signal intensity. The standard deviation of the distribution σ_I^2 is related by C_n^2 by

$$C_n^2 = 1.041 \cdot 10^{-14} \sigma_I$$

The measurement is susceptible to saturation, that is, an increase of turbulent intensity will not result in an increased standard deviation of the intensity distribution. The minimum intensity value for the occurrence of turbulence has been suggested by Crittenden to be at $\sigma^2 = 0.8$. For this value, the corresponding turbulent intensity is $C_n^2 = 6.6 \cdot 10^{-15}$ This value was not reached during the experiment.

5. SHIPBORNE MEASUREMENTS

The shipborne measurements consisted of bulk meteorological parameters and derived turbulence parameters. The latter measurements were taken to provide an indication of validity of the thermal and humidity components of the bulk model, if the model C_n^2 did not agree with optical measurements.

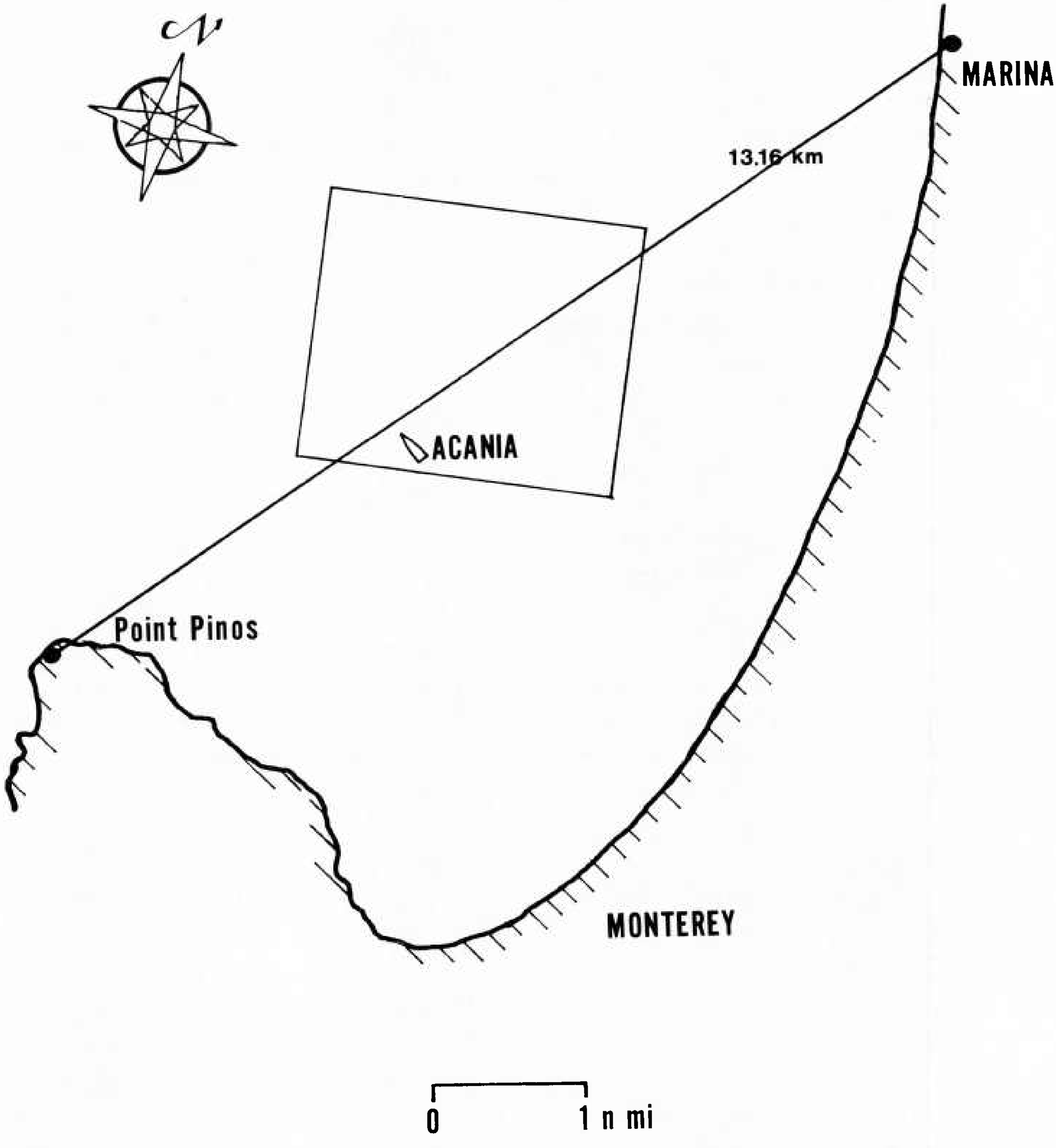


Figure 1. Map of Monterey Bay and optical range.

The bulk measurements consisted of cup anemometers and wind vanes for wind speed and direction. These were corrected for ship motion. Air temperature was measured at 4.2 m, 7.0 m and 19.6 m above the surface. Dew point was measured at 7.0 m, and humidity was measured at 19.6 m. Sea surface temperature was measured by a platinum thermometer maintained in the first 25 cm below the sea surface. The infrared sea surface temperature was measured by an infrared radiometer mounted on a 3 m boom on the ship's rail.

6. SATELLITE IMAGERY

GOES satellite imagery was stored on magnetic tape for the dates 28 April through 9 May 1980. The (western) GOES data was received at NEPRF at 1130 (PDT) daily and transferred to tape. The data was in the form of visual and infrared (8-12 μm) images, with 256 gray shades, and a resolution of .3 n mi.

The data was later analyzed as follows. Visual imagery was screened to determine which days were cloud free in the Monterey Bay vicinity. The corresponding IR data was magnified by a factor of 4 and displayed on the NEPRF SPADS (Satellite Processing and Display System). The gray shade contrast settings were adjusted until the sea surface temperature contrast was maximized. Two calibrations were used to relate temperature to gray shade - the first was a general calibration accurate to 1.0 degrees C, the second accurate to 0.5°C. The two resulting analyses are shown in Figures 2 and 3 respectively.

DMSP data was also collected. Several examples of anomalous gray shades occurred, where the DMSP image (0.4 - 1.1 μm sensitive range) shows contrasting regions, without cloud cover. The explanation of this phenomenon has been attributed to dryer regions, presence of smaller (drier) aerosols and different surface reflectivity (Fett and Isaacs, 1979).

A DMSP image, taken on 1 May 1980, shows a pronounced darker shade in the northern part of Monterey Bay. The darker shade indicates that less signal is being received at the detector. The shape of the darker region suggests that the shade is wind related.

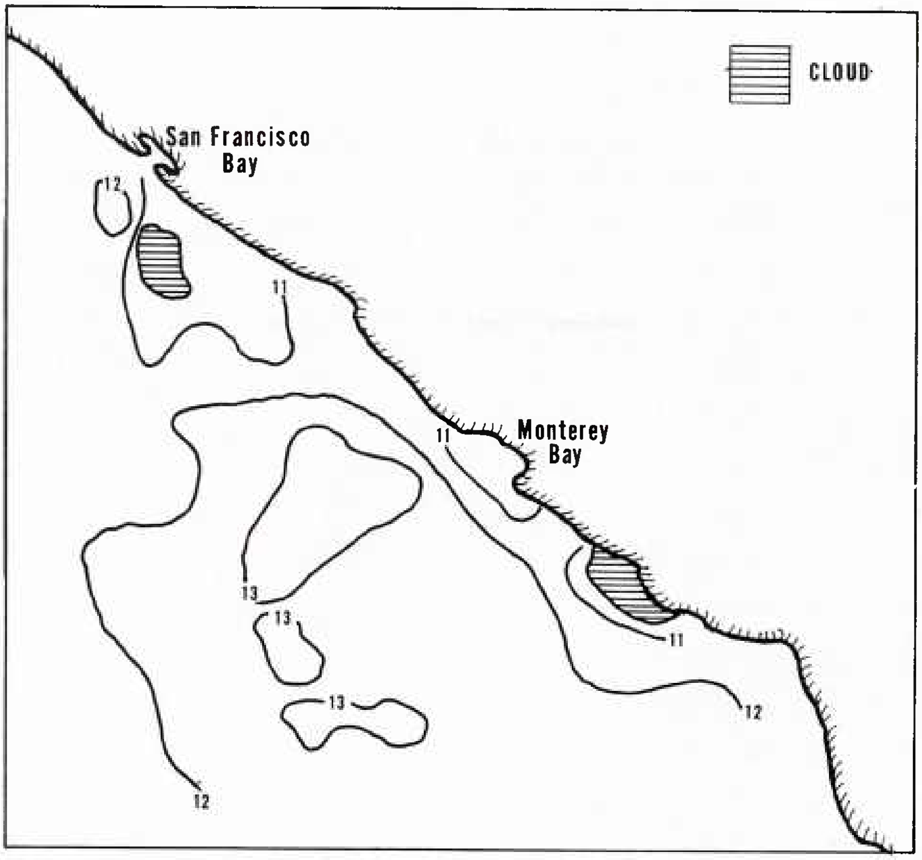


Figure 2. Analysis of GOES satellite data 1 May 1980.

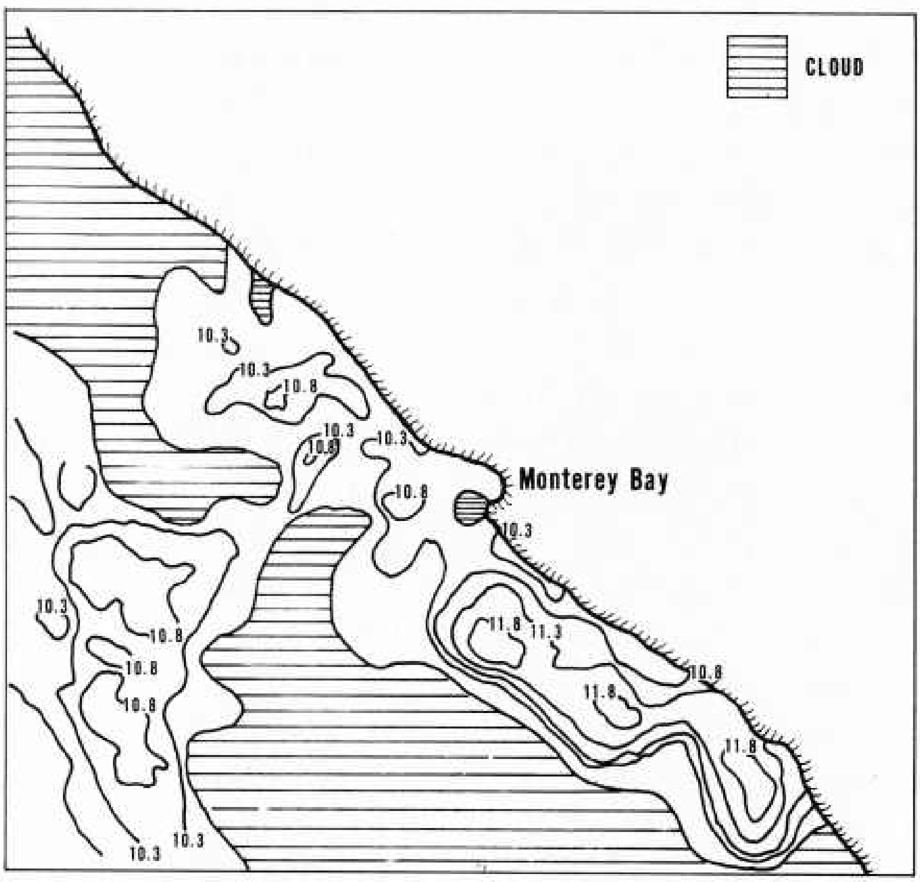


Figure 3. Analysis of GOES satellite data 7 May 1980.

Several possible mechanisms attenuate the signal. These include decrease of large aerosol concentration by drying overland and smoothing of the sea surface by the barrier of land upwind of the darker portion. The image is included as Fig. 4. These phenomena are being studied more extensively to explain the uncertainties of the image (Fett, R., personal communication).

7. WEATHER CONDITIONS

The basic weather conditions occurring during the entire experimental period were neutral. The neutral conditions were modified by several occurrences of moderately stable and moderately unstable conditions.

The upper air pattern is shown on the National Meteorological Center 500 mb charts (Figures 5-17). The California coastal region was characterized by a weak low pressure area remaining stationary from before the experiment to 6 May 1980. This stationary low was circled by serveral small weak cold fronts. Thus the synoptic flow was in general weak, with alternating periods of onshore and offshore flow. The onshore flow was generally accompanied by low level clouds, while offshore flow was cloud free.

These conditions started to be modified by the presence of a strong low pressure area off the British Columbia coast. This was responsible for the clearer conditions at the end of the experiment. The cold front passed the Monterey Bay area after the experimental period ended.

8. RESULTS

The index of refraction structure function, C_n^2, measured by the optical means, was compared to the C_n^2 predicted by the workshop model. The range of optical C_n^2 was limited to relatively low values because of the neutral and near neutral conditions.

The analysis separated the data into three groups, as suggested by the Davidson, et al (1980) report. These groups were (a) unstable, homogeneous sea surface temperature conditions, (b) stable homogeneous sea surface temperature, and (c) stable conditions. The inhomogeneous sea surface temperature conditions were

Figure 4. DMSP (0.4 - 1.1 μm) imagery of Monterey Bay, 1130 PDT, 1 May 1980.

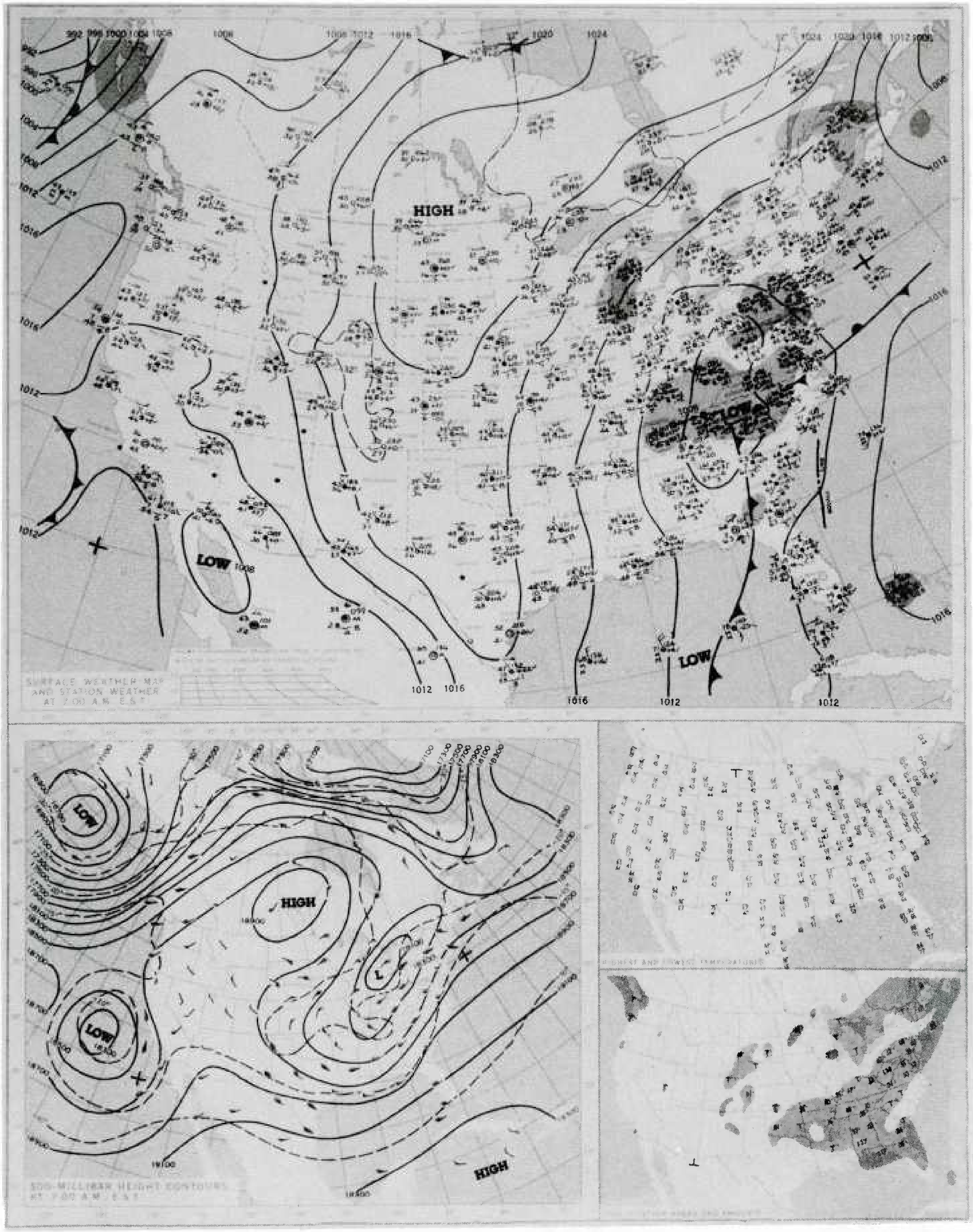


Figure 5. National Meteorological Center surface and 500 mb analyses, 27 April 1980.

MONDAY, APRIL 28, 1980

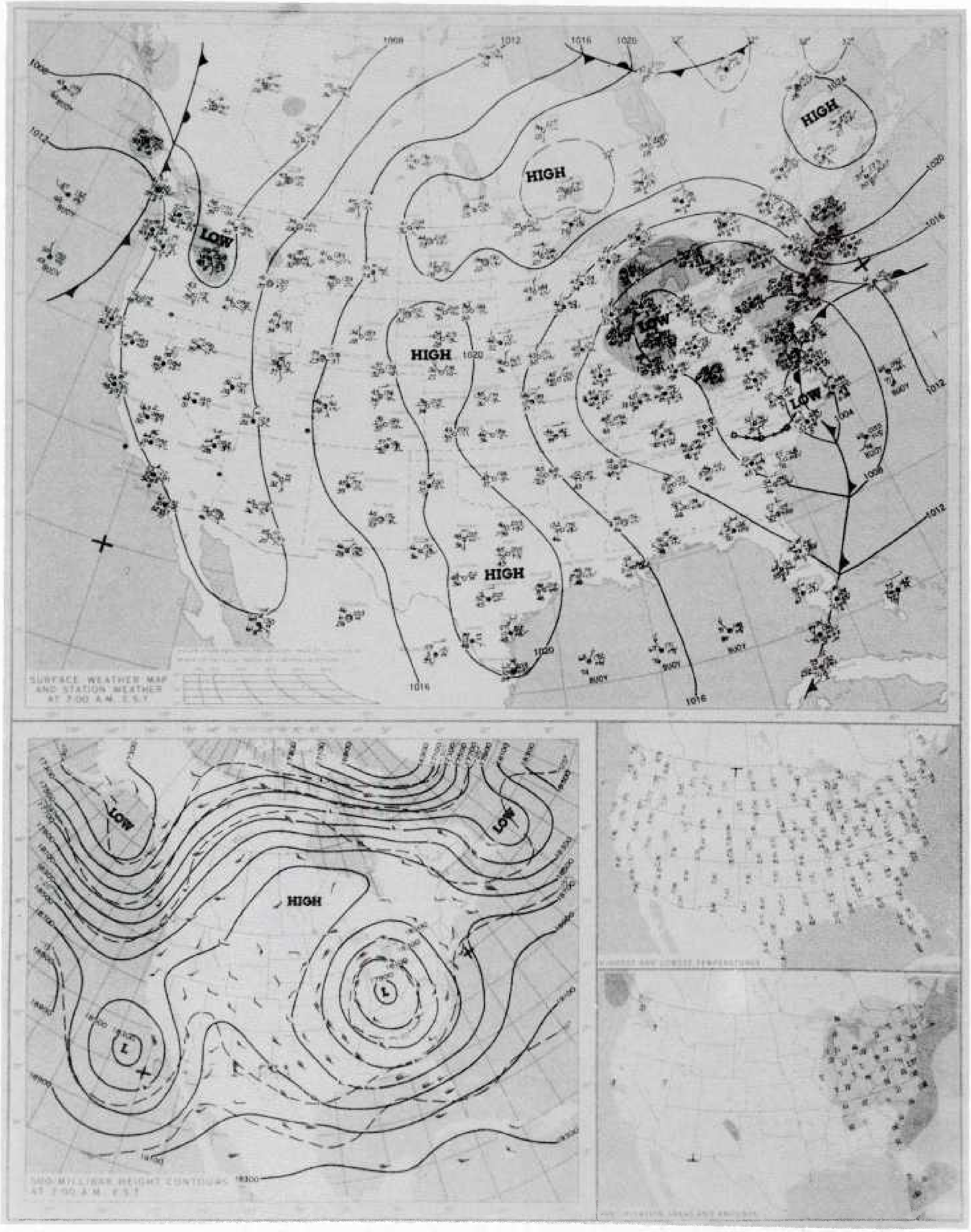


Figure 6. National Meteorological Center surface and 500 mb analyses, 28 April 1980.

TUESDAY, APRIL 29, 1980

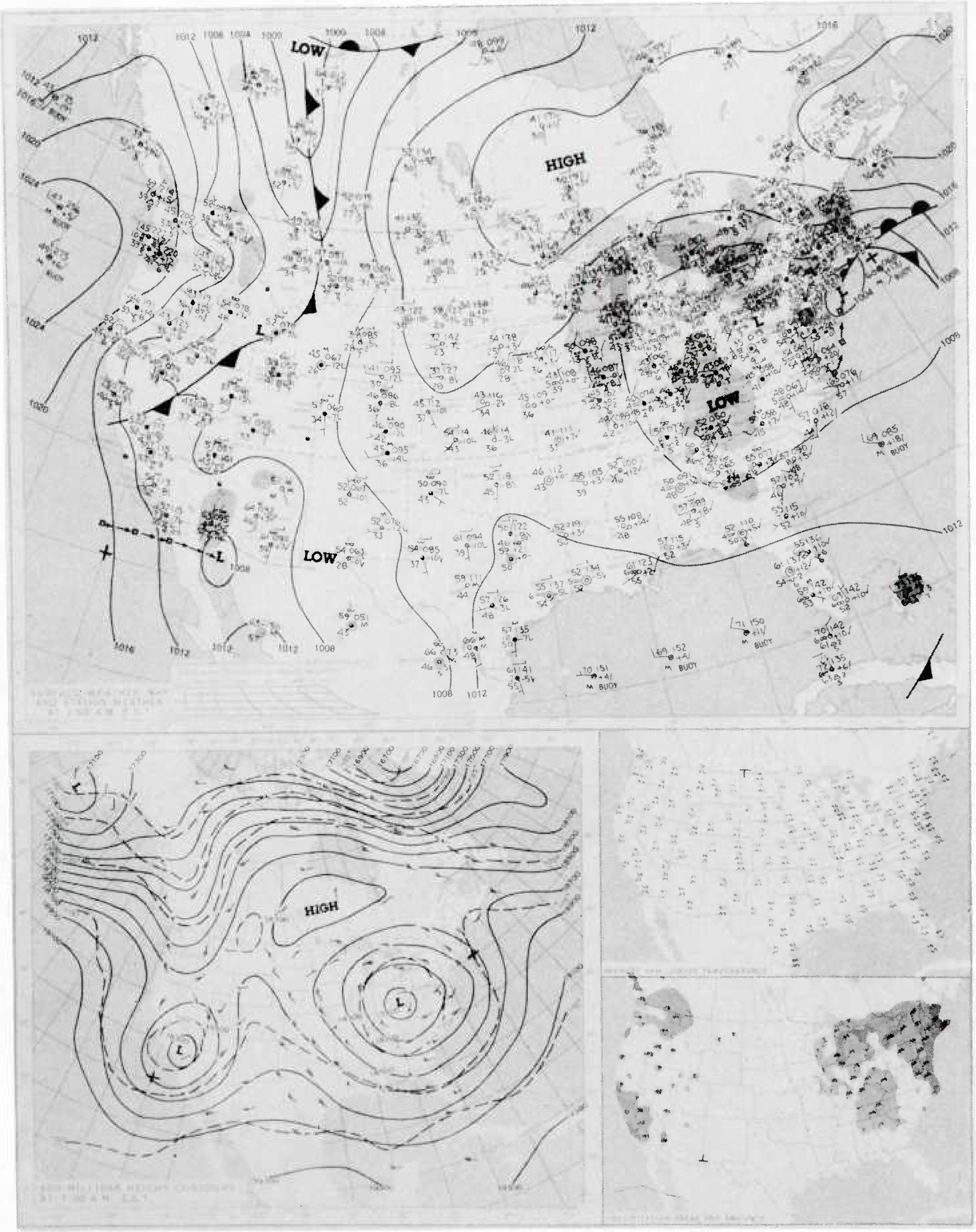


Figure 7. National Meteorological Center surface and 500 mb analyses, 29 April 1980.

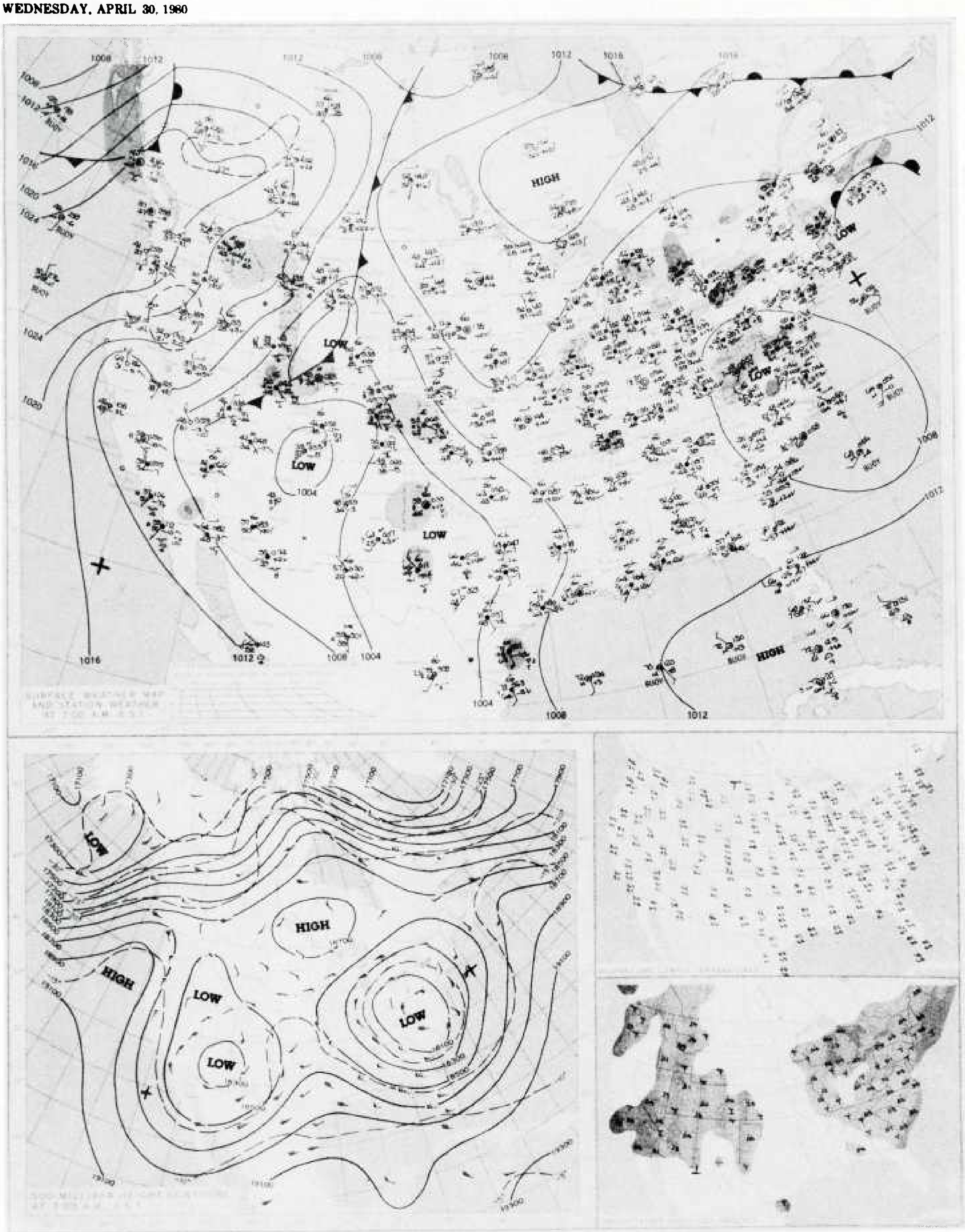


Figure 8. National Meteorological Center surface and 500 mb analyses, 30 April 1980.

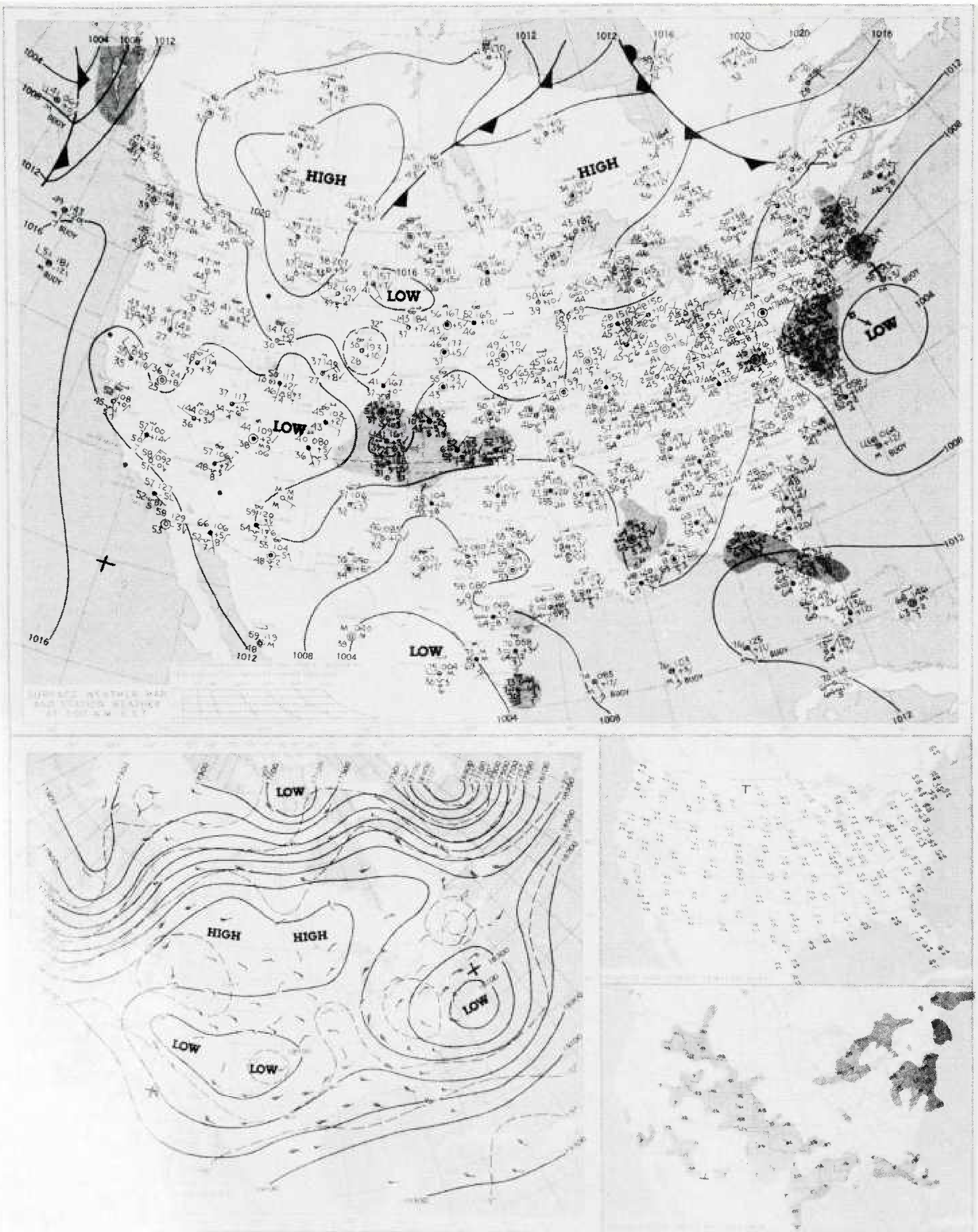


Figure 9. National Meteorological Center surface and 500 mb analyses, 1 May 1980.

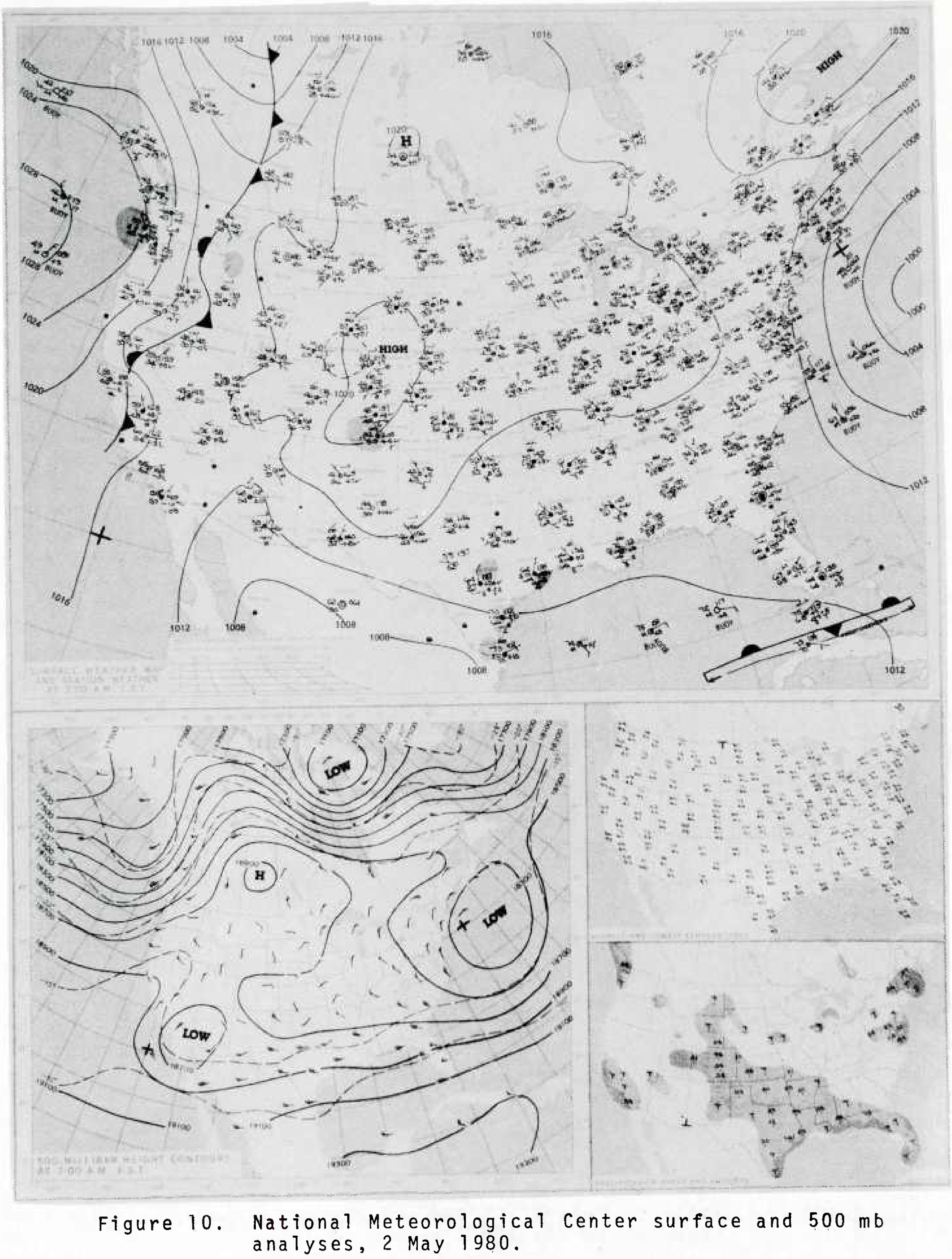


Figure 10. National Meteorological Center surface and 500 mb analyses, 2 May 1980.

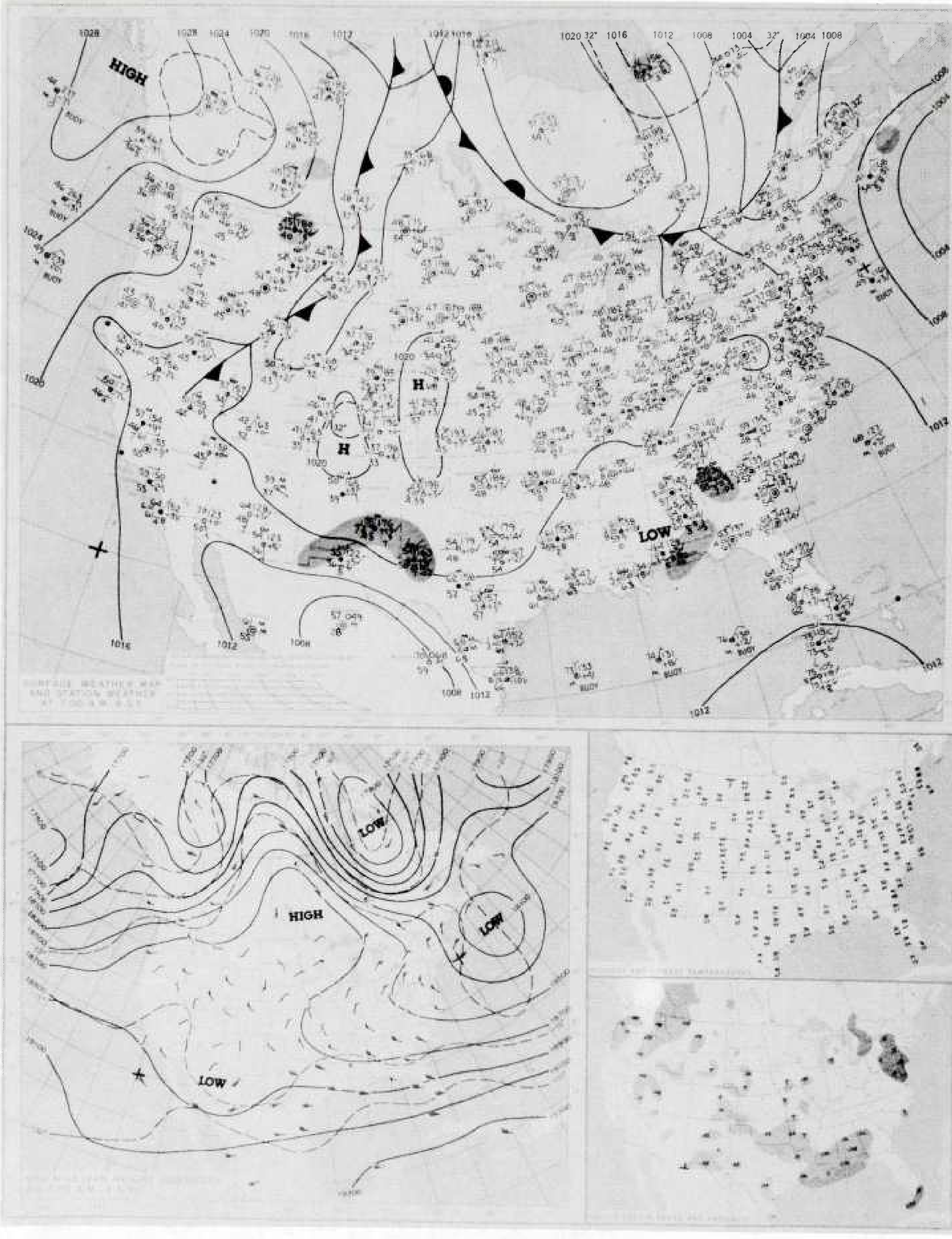


Figure 11. National Meteorological Center surface and 500 mb analyses, 3 May 1980.

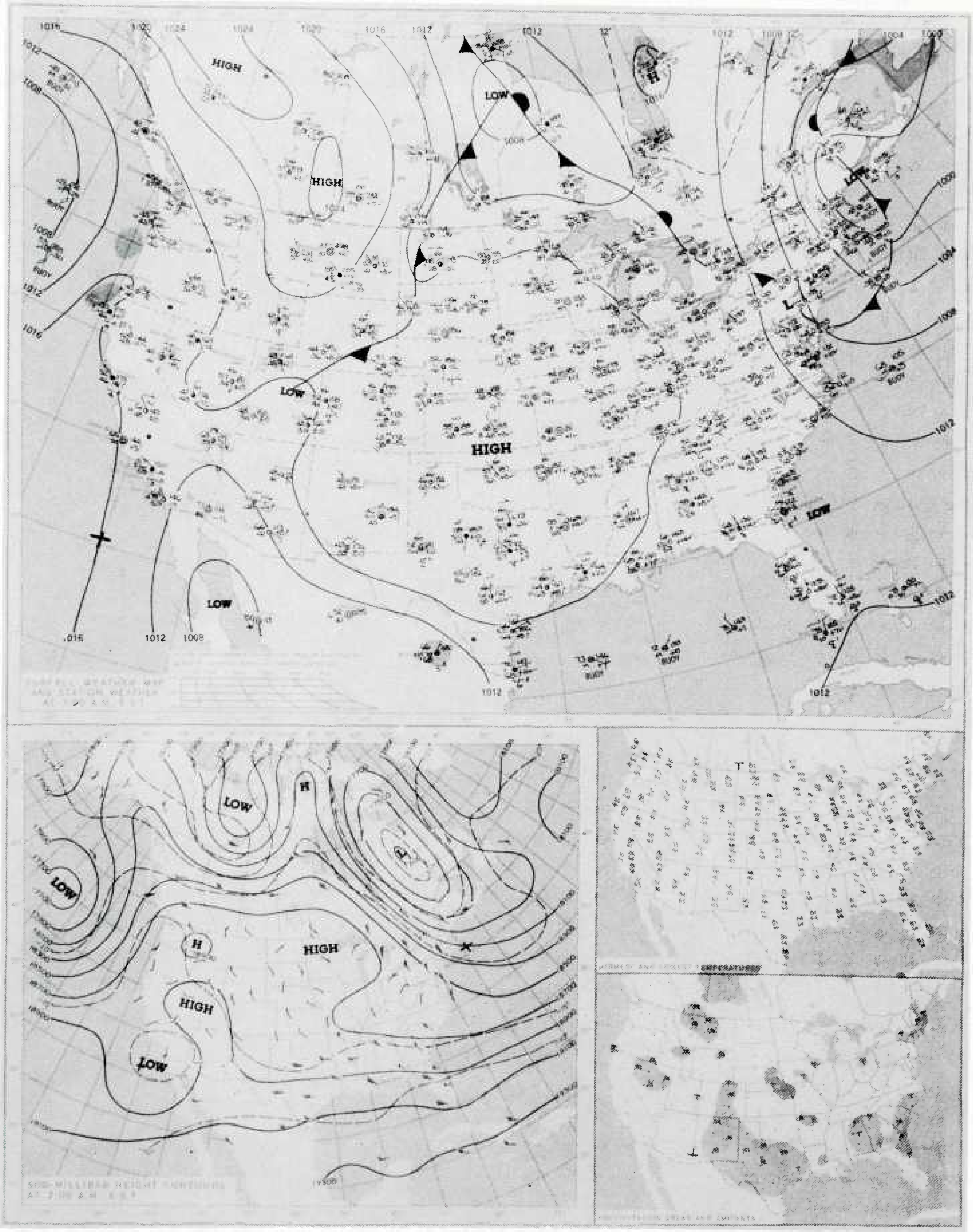


Figure 12. National Meteorological Center surface and 500 mb analyses, 4 May 1980.

MONDAY, MAY 5, 1980

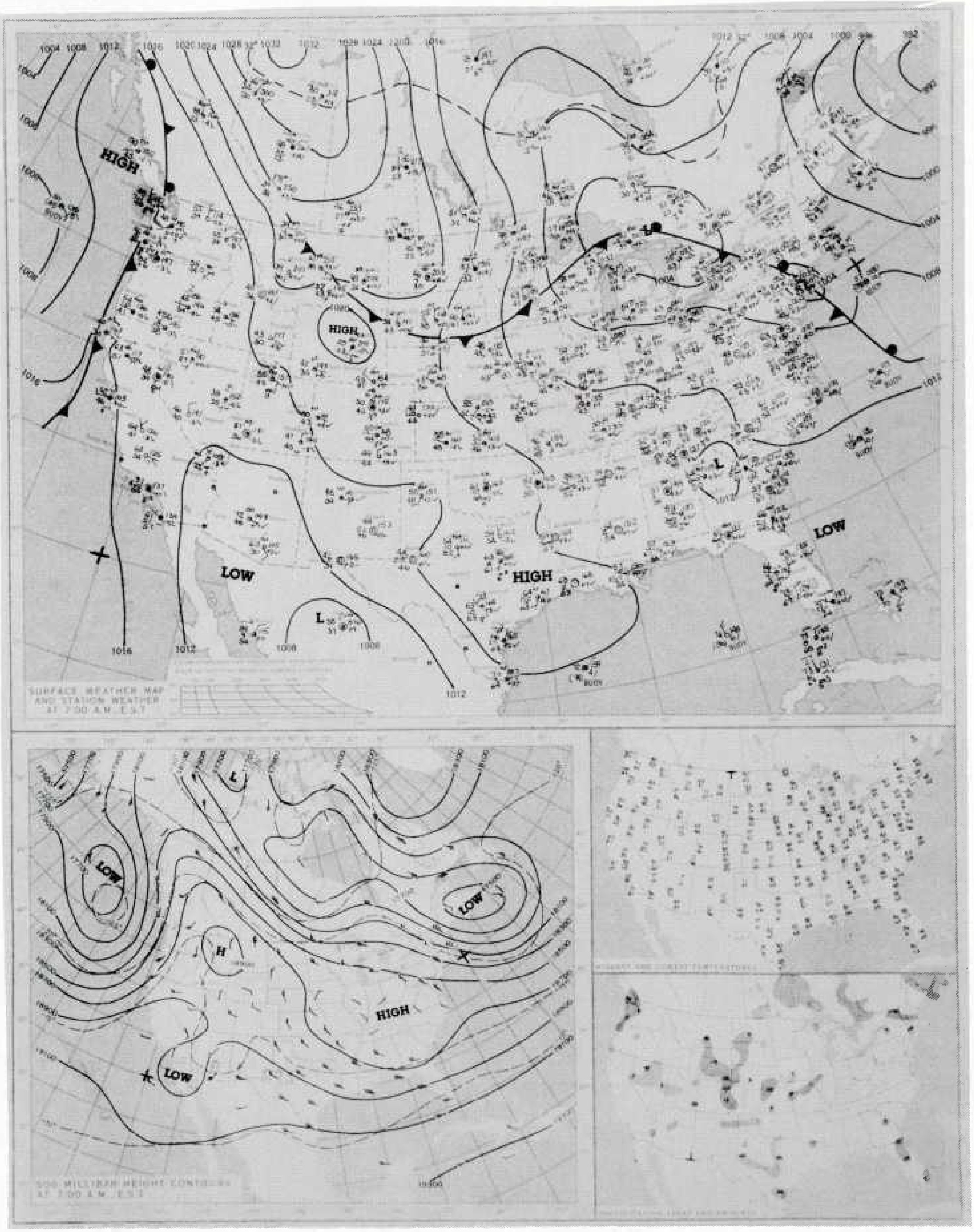


Figure 13. National Meteorological Center surface and 500 mb analyses, 5 May 1980.

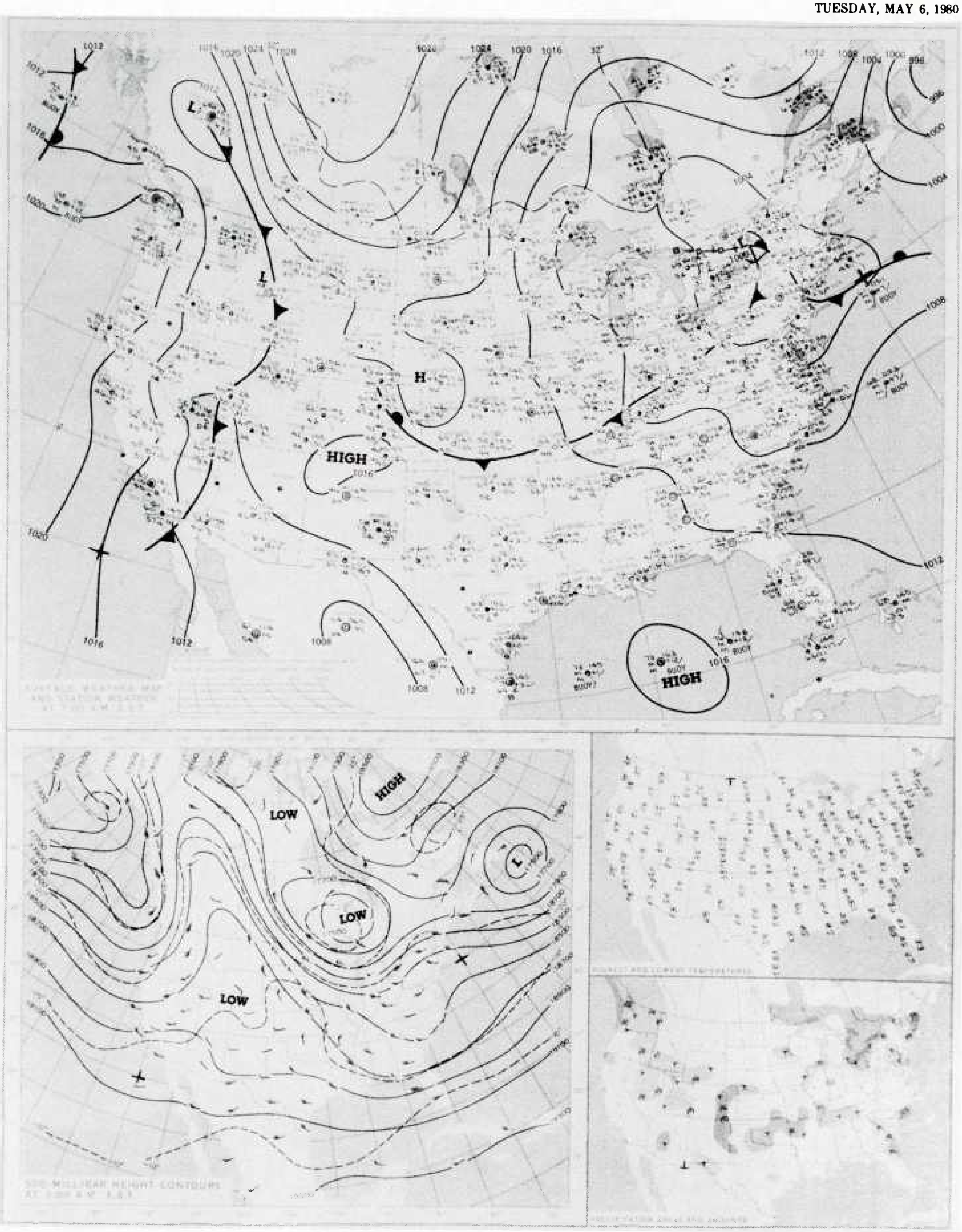


Figure 14. National Meteorological Center surface and 500 mb analyses, 6 May 1980.

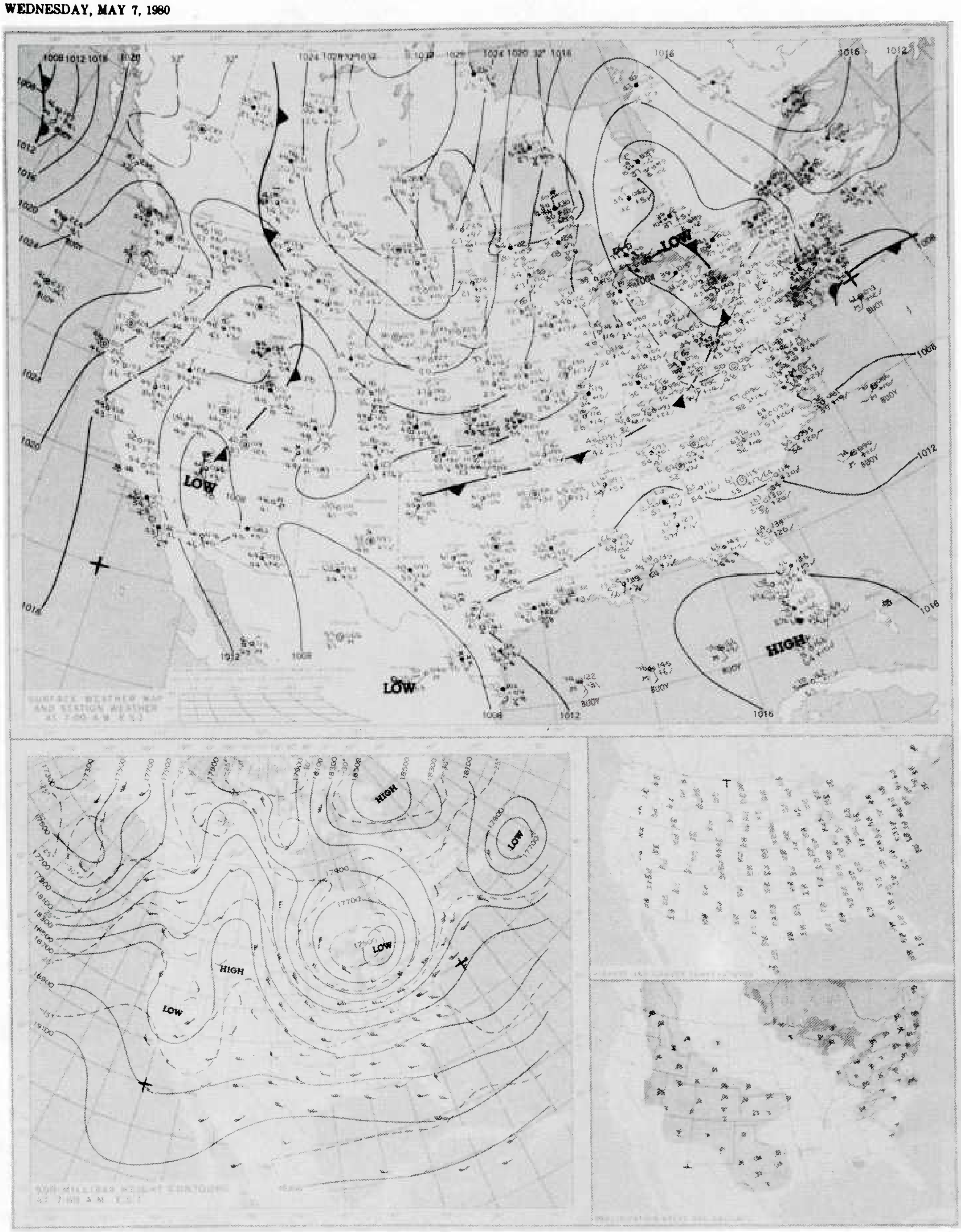


Figure 15. National Meteorological Center surface and 500 mb analyses, 7 May 1980.

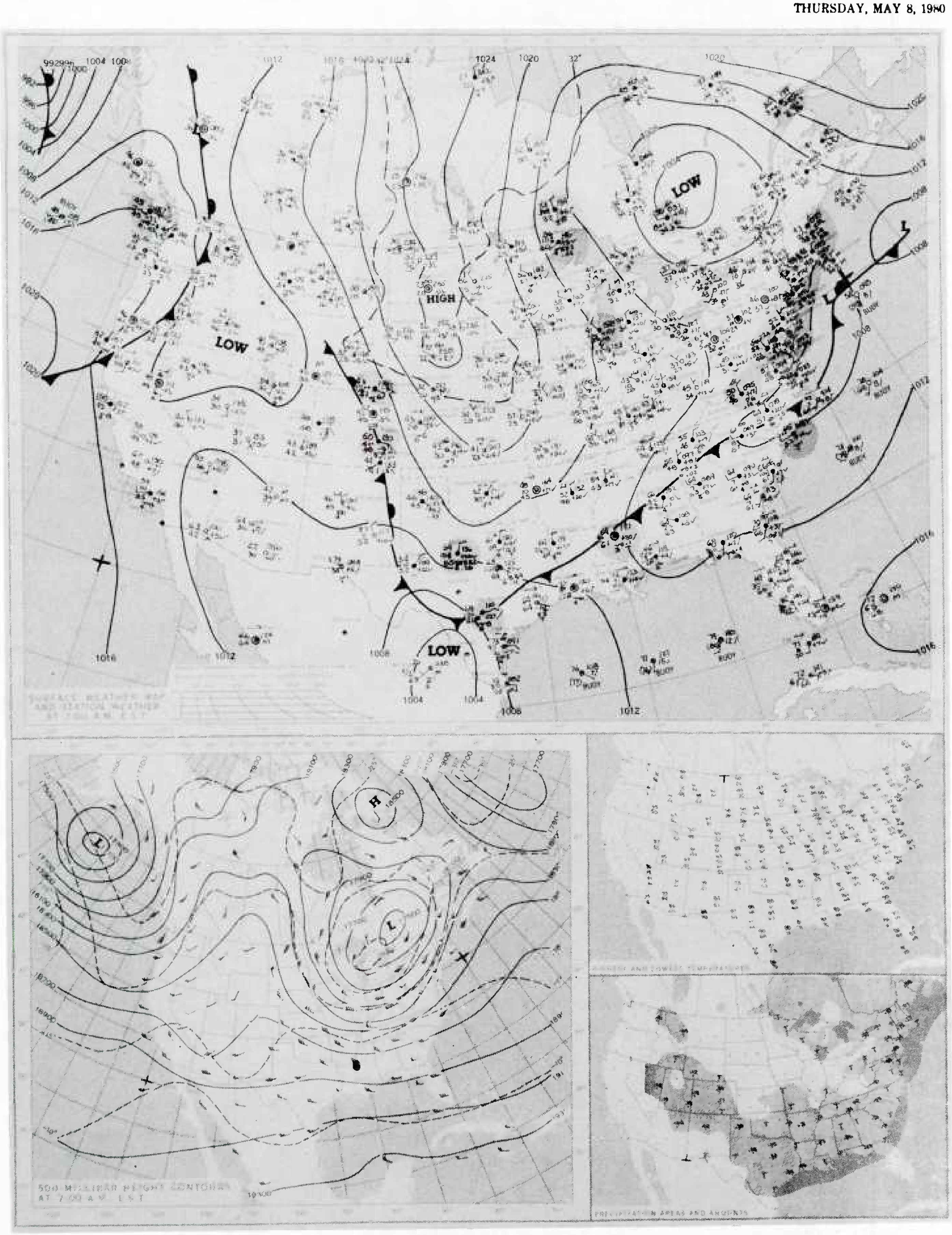


Figure 16. National Meteorological Center surface and 500 mb analyses, 8 May 1980.

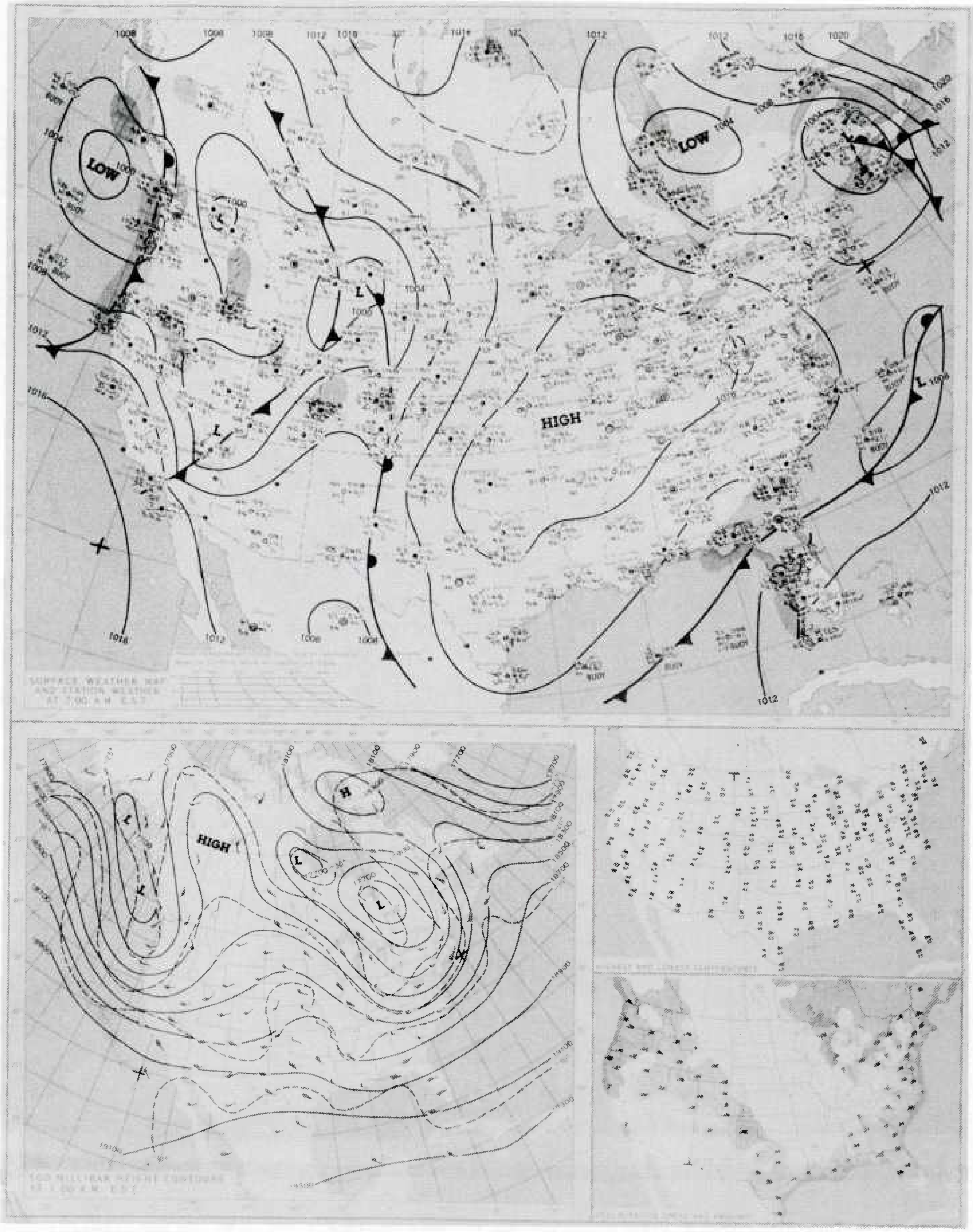


Figure 17. National Meteorological Center surface and 500 mb analyses, 9 May 1980.

those in which there seemed to be a 1°C to 2°C warming of the sea surface temperature under the optical path compared to the temperature farther from shore in the bay.

Both optical and model results had a certain amount of uncertainty involved in the measurements. The optical C_n^2 had an uncertainty in evaluating the standard deviation of the intensity distribution. This uncertainty showed up in near simultaneous measurements having a maximum of about 15% difference in C_n^2. Similarly the model result also was uncertain because of sea surface temperature uncertainty. The uncertainty in air sea temperature difference of 0.2 degrees results in a 12% uncertainty in the value of C_n^2.

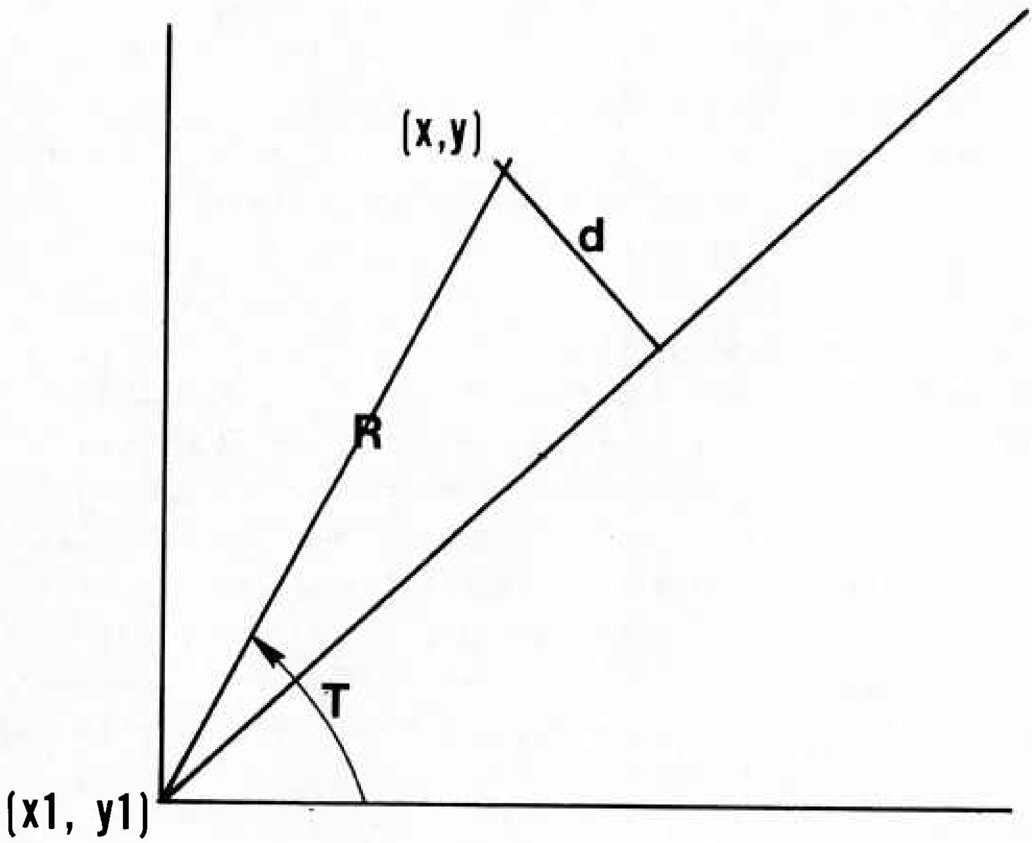
A geometric method was chosen to compare logarithms of the measured and model values of C_n^2. The method basically calculates the perpendicular "distance" from each observation to the line corresponding to identical model and measured C_n^2 values (see Fig. 18). This distance was calculated for all measurements and the mean d and standard deviation s of the logarithm of the distribution was evaluated. The latter two numbers provided a quantitative measure of how well the optical measurements and the model provided the same results.

The optical data were compared to the model results using platinum wire sea surface temperatures ("bucket") and the infrared derived temperatures. These comparisons used sea surface temperatures with and without the sea surface corrections described in Section 2. The results are shown in Figures 19-22. The optical C_n^2 were also compared to C_n^2 evaluated from shipborne C_T^2 measurements in Figure 23.

9. CONCLUSIONS

The comparison of optical and model results in Figure 23 shows good agreement of the two sets of C_n^2 values. In particular, the figures indicate that 66% of data had the optical data within a factor of 2.1 of the model. The 97% and 99% confidence intervals were factors of 4.8 and 10.5 respectively.

The addition of the sea surface temperature correction makes only a slight difference on the agreement of model and measurement.



$$d = R * \sin(T - \pi/4)$$

$$R = ((x - x_1)^2 + (y - y_1)^2)^{1/2}$$

$$T = \arctan((y - y1)/(x - x1))$$

Figure 18. Geometry of data comparison.

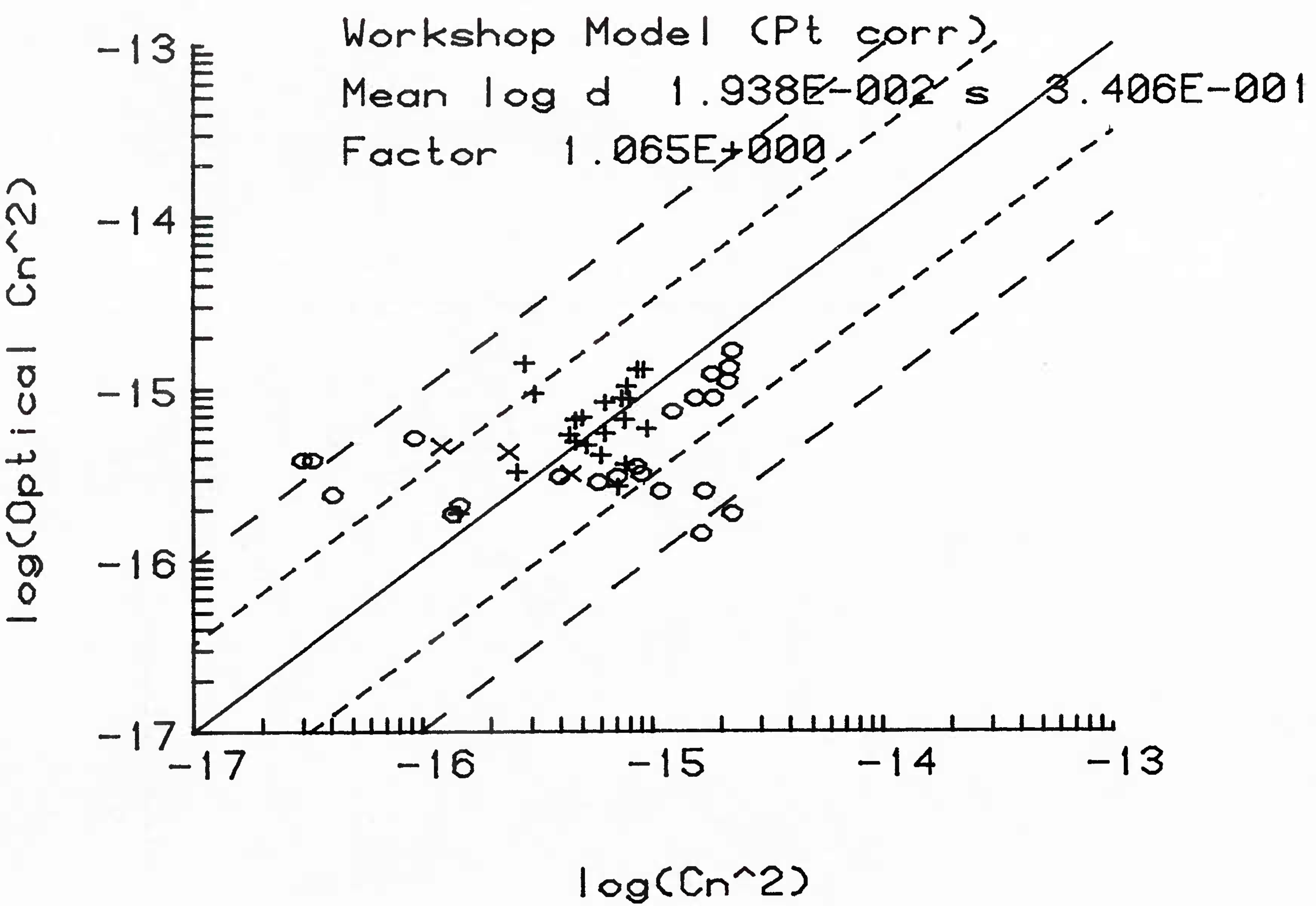


Figure 19. Comparison of optical C_n^2 to workshop model (Corrected Pt bucket temperature). Solid line is where both are identical; short dash and long dash are one and two standard deviation intervals, respectively. Symbols are (+) homogeneous unstable conditions; (o) inhomogeneous unstable conditions; and (x) homogeneous stable conditions.

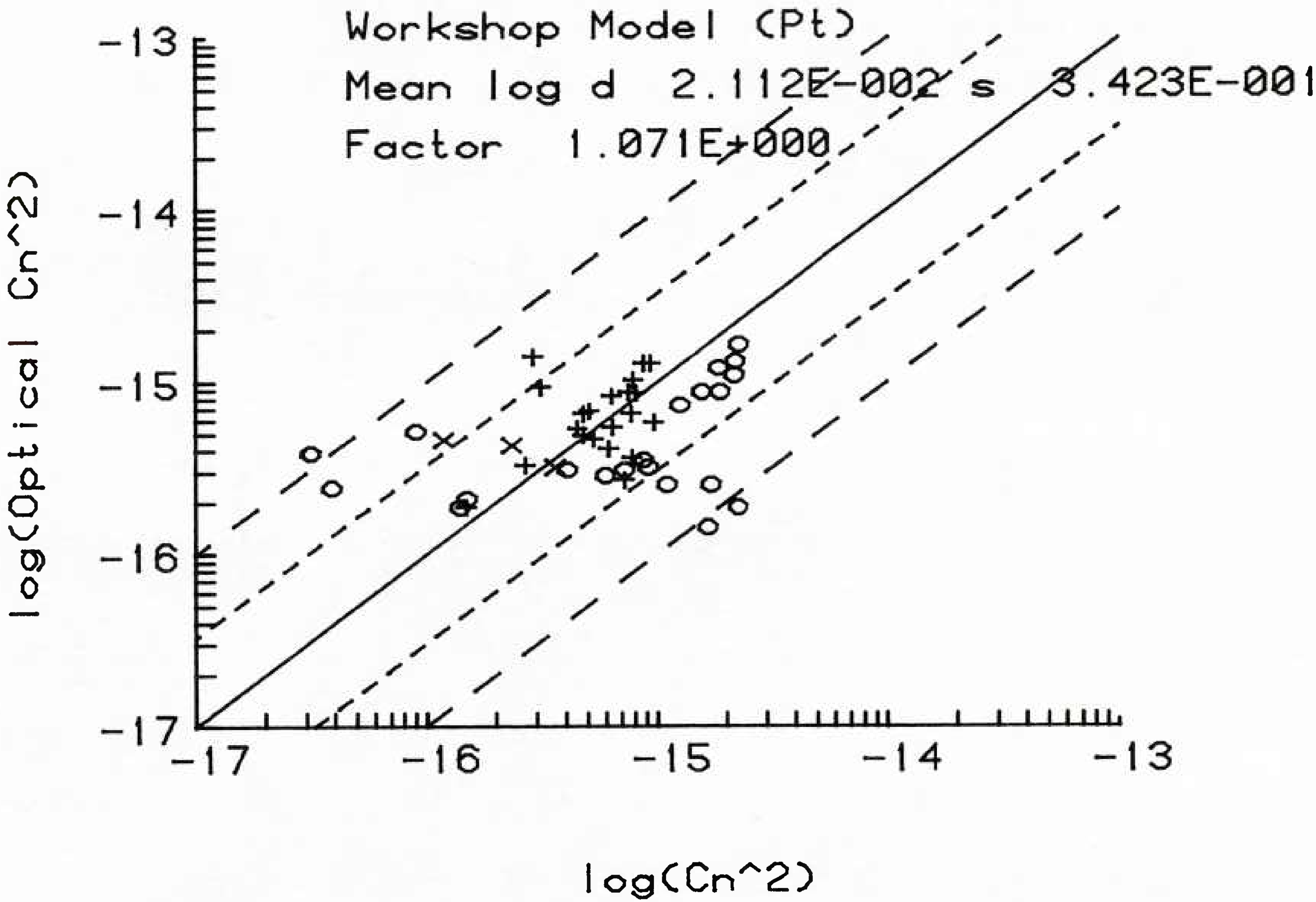


Figure 20. Comparison of optical C_n^2 to workshop model (uncorrected Pt temperature).

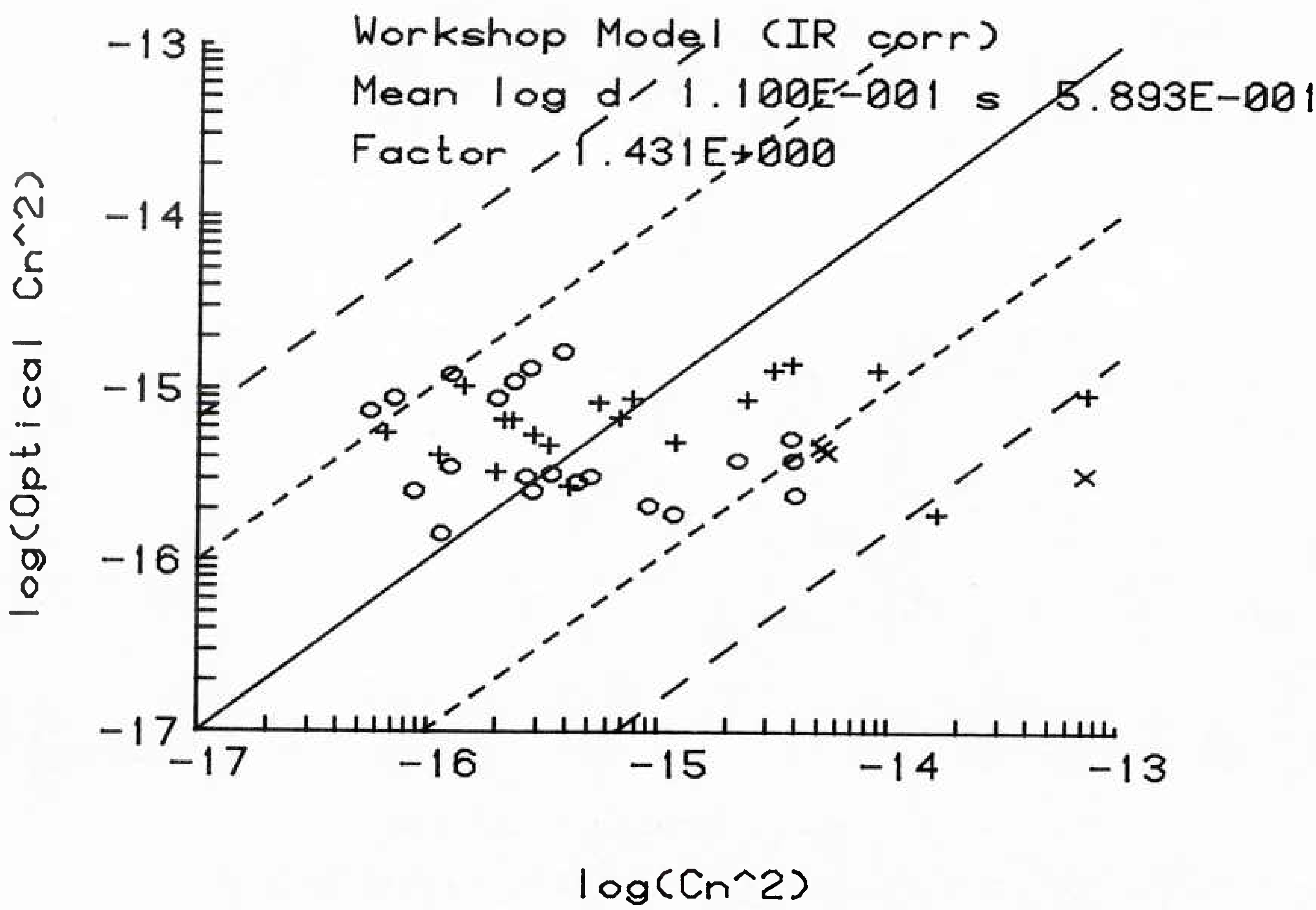


Figure 21. Comparison of optical C_n^2 to workshop model (corrected IR temperature).

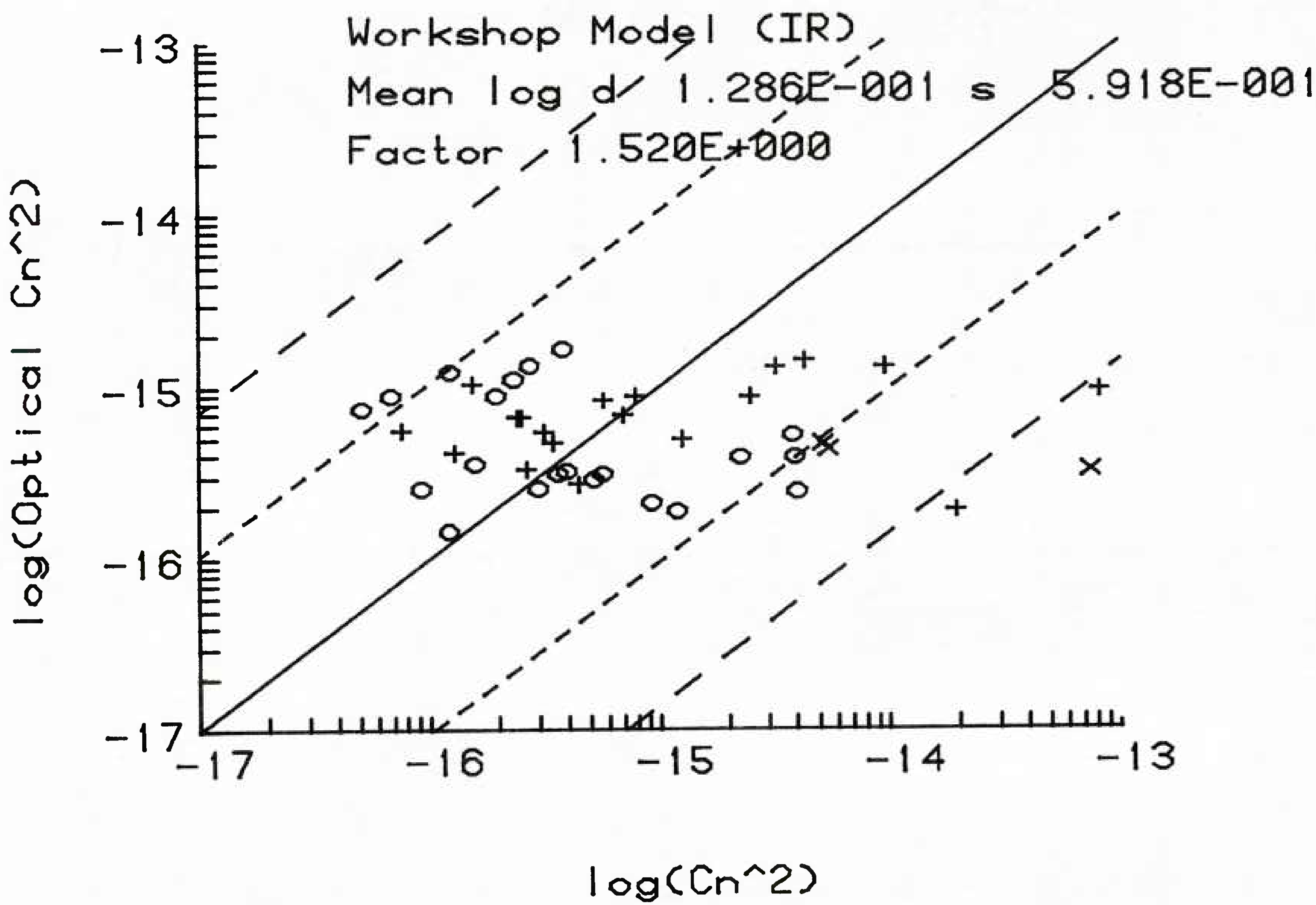


Figure 22. Comparison of optical C_n^2 to workshop model (uncorrected IR temperature).

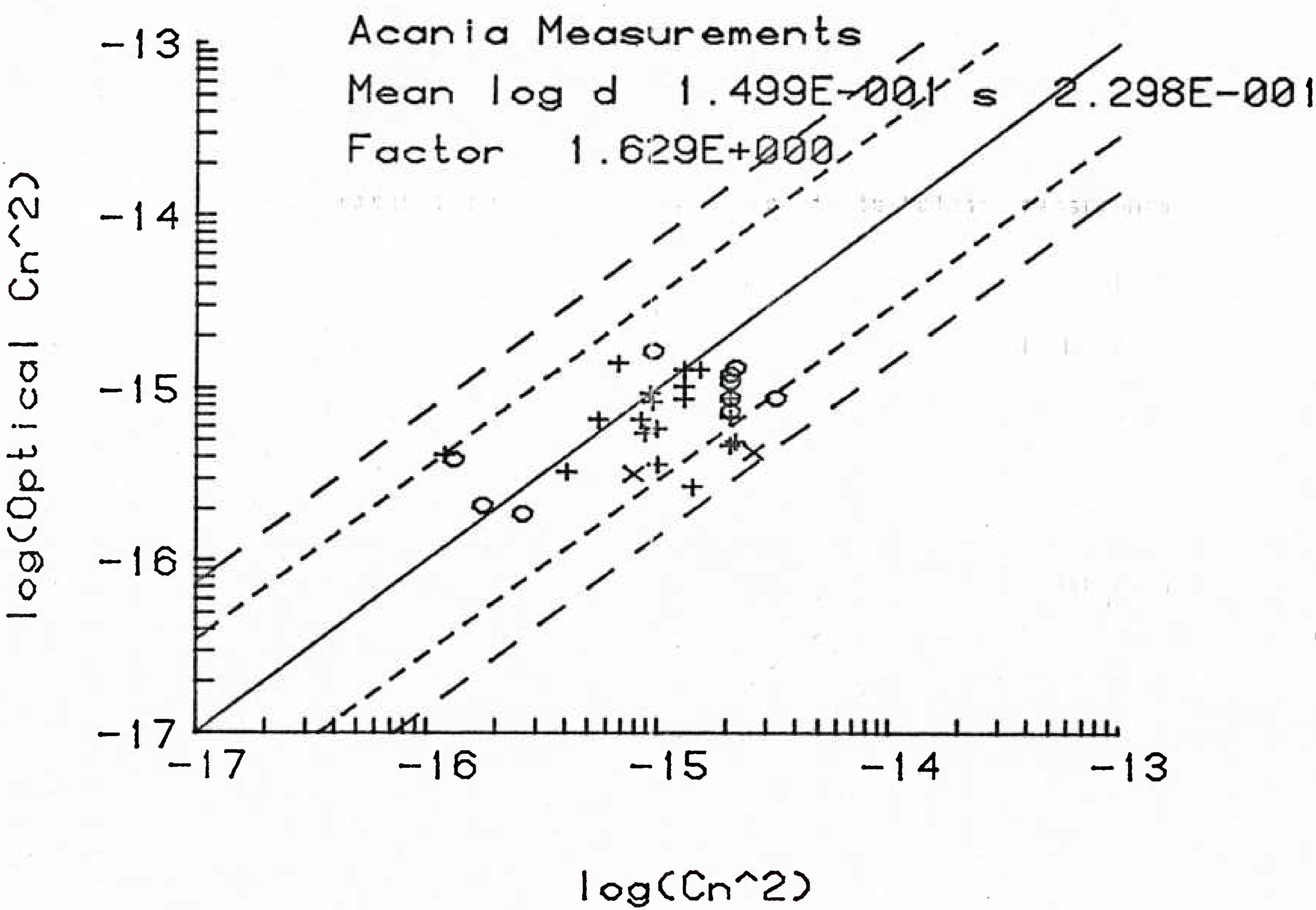


Figure 23. Comparison of optical C_n^2 to Acania turbulence measurements.

The mean and standard of the model and measured differences changed only in the second and third significant figures. Based on these results, the addition of the temperature correction does not benefit the bulk C_n^2 model.

The comparison of optical C_n^2 and that derived from infrared sea surface temperatures shows little agreement between the two. This occurred regardless of whether the surface temperature correction was included. The compared to the bucket temperature, IR measurement seemed to have a bias which could not be handled by the model, resulting in C_n^2 which had no correlation to the optical measurements. Further work should be conducted to analyze the reasons for the bias in temperatures, and the possibility of formulating a model of sea surface temperature bias for the bulk C_n^2 model.

The satellite derived IR temperatures were in agreement with the ship IR surface temperatures, more than with the bucket temperatures. The development of a bias model would possibly enable use of satellite infrared temperature data as an aid to mesoscale C_n^2 evaluation.

All the above conclusions are based on this data set, which was limited to near-neutral stability conditions. The credibility of the C_n^2 model (based on land measurements and model development) is best in unstable conditions, less good in neutral and least in stable conditions. Based on the experimental comparisons, the bulk model is shown calculating optical C_n^2 with accuracy in neutral conditions. By inference, we can say that in very unstable conditions the model calculation would be better. For ultimate verification however the model should be validated in very turbulent conditions, both stable and unstable.

Acknowledgments

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